Dipion decays of heavy baryons*

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Abstract: Compared with the charmed baryons, the bottom baryons are not very well known, either experimentally or theoretically. In this paper, we investigate the dipion strong decays of the P-wave and D-wave excited bottom baryons in the framework of the QPC model. We also extend the same analysis to the charmed baryons.

Key words: bottom baryon, charmed baryon, dipion decay, the quark pair creation model

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1 Introduction

In 2013, the LHCb Collaboration reported the observations of two Λ_b^{*0} states with the spin-parity quantum numbers $J^P=1/2^-$ and $3/2^-$, separately, which are identified as the orbitally excited states of Λ_b^0 [1]. These observations not only enrich the bottom baryon family but also provide important clues to further theoretical and experimental investigations of the bottom baryons.

Compared with the rich charmed baryon family, the bottom baryons remain largely unexplored, either experimentally or theoretically. Experimentally, in addition to the Λ_b^0, the Ξ_b^- baryon with the quark content bsd was observed by the D0 [2] and CDF [3] collaborations in 2007. Later, the D0 and CDF collaborations observed the doubly-strange Ω_b^- baryon [4, 5]. Then, the CDF Collaboration observed the ground state Ξ_b^0(bsu) with the beauty-strange content [6], and the CMS Collaboration reported the corresponding excited state, Ξ_b^{0*} with $J^P=3/2^+$ [7]. Among the triplets $\Sigma_b^{\pm0}$ with spin $J=1/2$ and $\Sigma_b^{*\pm,0}$ with $J=3/2$, only the charged states $\Sigma_b^{(*)\pm}$ were observed in the $\Lambda_b^0\pi^\pm$ decay modes [8, 9]. Theoretically, the two-body strong decay width of the charmed baryons was investigated several year ago in Refs. [10, 11]. However, the three-body strong decays of the heavy baryons are still unexplored at present.

The experimental progress on the bottom baryons has stimulated theorists' extensive interest in studying their properties [12, 13]. In order to understand the structure of heavy baryons systematically and provide valuable information for the further experimental exploration, in this work we shall study the dipion decays of the excited bottom baryons. The dipion decays are the typical tree-body decays. We adopt the quark pair creation (QPC) model. We also extend the same formalism to calculate the dipion decay width of the charmed baryons. The mass and the corresponding observed decay channel of the bottom baryons are collected in Table 1, while the three-body dipion decays of the charmed baryons and their corresponding partial decay widths are listed in Table 2.

In this work, we calculate a special class of the three-body dipion strong decays of heavy baryons. That is, a heavy baryon decays into 2π plus another heavy baryon, where the quantum number of the 2π system is either $I(J^P)=0(0^+)$ or $I(J^P)=1(1^-)$, which correspond to the

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intermediate states σ(600) and ρ(770), respectively. Thus, the main task is to calculate the two-body strong decays of the heavy baryons, where the final states must contain ρ(770) or σ(600). In the next section, we illustrate the calculation details.

This paper is organized as follows. After the introduction, we present the the formalism of the three-body dipion strong decays of the heavy baryons. In Section 3, the numerical results are given. The last section is the discussion and conclusion.

Table 1. The mass and discovery channels of the bottom baryons. Here, we use "–" to denote the case when no strong decay channel is observed experimentally. The masses are in unit of MeV.

states	$I(J^P)$	mass	experiment channel
Λ_b^{0*}	$0\left(\frac{1}{2}^-\right)$	5912.0±0.6	$\Lambda_b^0\pi^+\pi^-$ [1]
Λ_b^{0*}	$0\left(\frac{3}{2}^-\right)$	5919.8±0.6	$\Lambda_b^0\pi^+\pi^-$ [1]
Σ_b^+	$1\left(\frac{1}{2}^+\right)$	5811.3±1.9	$\Lambda_b^0\pi^+$ [8, 9]
Σ_b^-	$1\left(\frac{3}{2}^+\right)$	5815.5±1.8	$\Lambda_b^0\pi^-$ [8, 9]
Σ_b^{*+}	$1\left(\frac{1}{2}^+\right)$	5832.1±1.9	$\Lambda_b^0\pi^+$ [8, 9]
Σ_b^{*-}	$1\left(\frac{3}{2}^+\right)$	5835.1±1.9	$\Lambda_b^0\pi^-$ [8, 9]
Ξ_b^0	$\frac{1}{2}\left(\frac{1}{2}^+\right)$	5788±5	– [6]
Ξ_b^-	$\frac{1}{2}\left(\frac{1}{2}^+\right)$	5791±2.2	– [2, 3]
Ξ_b^{0*}	$\frac{1}{2}\left(\frac{3}{2}^+\right)$	5945±2.3	$\Xi_b^-\pi^+$ [7]

Table 2. A summary of the experimental three-body dipion decay widths of the charmed baryons in unit of MeV.

states	$I(J^P)$	decay width	experiment channel
$\Lambda_c(2595)^+$	$0\left(\frac{1}{2}^-\right)$	2.6±0.6	$\Lambda_c^+\pi^+\pi^-$[14]
$\Lambda_c(2625)^+$	$0\left(\frac{3}{2}^-\right)$	<0.97	$\Lambda_c^+\pi^+\pi^-$[14]
$\Lambda_c(2880)^+$	$0\left(\frac{5}{2}^+\right)$	5.8±1.1	$\Lambda_c^+\pi^+\pi^-$ [15]
$\Xi_c(2815)^+$	$\frac{1}{2}\left(\frac{3}{2}^-\right)$	<3.5	$\Xi_c^+\pi^+\pi^-$ [16]
$\Xi_c(2815)^0$	$\frac{1}{2}\left(\frac{3}{2}^-\right)$	<6.5	$\Xi_c^0\pi^+\pi^-$ [16]

2 The three-body dipion decays of the bottom baryons

We adopt the same notation for the excited heavy baryons as in Ref. [10]. The heavy baryon contains one heavy quark (charm or bottom) and two light quarks (u, d or s), which can be categorized into either the symmetric 6_F or antisymmetric $\bar{3}_F$ flavor representation. For the S-wave heavy baryon, the total orbital-flavor-spin wave function is symmetric while its color wave function is antisymmetric. This fact indicates that the spin of the two light quarks is either $S=1$ for 6_F or $S=0$ for $\bar{3}_F$. Thus, the spin-parity quantum numbers of the S-wave heavy baryons are $J^P=\frac{1}{2}^+$ or $\frac{3}{2}^+$ for 6_F and $J^P=\frac{1}{2}^+$ for $\bar{3}_F$. Similarly, we can discuss the P-wave and D-wave heavy baryons. The detailed notations of the S-wave, P-wave and D-wave heavy baryons can be found in Figs. 1–3 of Ref. [10].

It is difficult to describe the hadron properties, such as the strong decay process, based on the first principle of QCD. Instead, we have to rely on different phenomenological models to investigate the properties of the abundant hadronic states. Among these phenomenological models, the quark pair creation (QPC) model, which was built by Micu [17] and further developed by Yaouanc et al. [18–22], has been extensively applied to study the Okubo-Zweig-Iizuka-allowed strong decays of hadrons[23–32].

In the QPC model, a pair of the flavor-singlet and color-singlet light quarks and antiquarks are created from the vacuum, which has the vacuum quantum number $J^{PC}=0^{++}$. In the non-relativistic limit, the transition operator is expressed as

$$
\begin{aligned}
T = & -3\gamma\sum_m\langle 1m;1-m|00\rangle\int \mathrm{d}^3\boldsymbol{k}_4 d^3\boldsymbol{k}_5\delta^3(\boldsymbol{k}_4+\boldsymbol{k}_5)\\
&\times\mathcal{Y}_1^m\left(\frac{\boldsymbol{k}_4-\boldsymbol{k}_5}{2}\right)\chi^{45}_{1,-m}\varphi_0^{45}\omega_0^{45}b^\dagger_{4i}(\boldsymbol{k}_4)d^\dagger_{5j}(\boldsymbol{k}_5), \quad (1)
\end{aligned}
$$

where i and j are the color indices of the created quark-antiquark pair, and $\varphi_0^{45}=(\mathrm{u\bar{u}+d\bar{d}+s\bar{s}})/\sqrt{3}$ and $\omega_0^{45}=\delta_{ij}$ denote the flavor and color wave functions, respectively, while $\chi^{45}_{1,-m}$ is the spin wave function with the spin angular momentum $(1,-m)$. $\mathcal{Y}_\ell^m(\boldsymbol{k})=|\boldsymbol{k}|^\ell Y_\ell^m(\theta_k,\phi_k)$ is the ℓ-th solid harmonic polynomial for the momentum-space distribution of the quark-antiquark pair. The dimensionless parameter γ describes the strength of the quark-antiquark pair creation from the vacuum.

For the convenience of the calculation, one usually takes the mock hadron states as follows

$$
\begin{aligned}
&|A(n_A^{2S_A+1}L_{AJ_AM_{J_A}})(\boldsymbol{P}_A)\rangle\\
&= \sqrt{2E_A}\sum_{M_{L_A},M_{S_A}}\langle L_AM_{L_A}S_AM_{S_A}|J_AM_{J_A}\rangle\\
&\times\int \mathrm{d}^3\boldsymbol{k}_1\mathrm{d}^3\boldsymbol{k}_2\mathrm{d}^3\boldsymbol{k}_3\delta^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3-\boldsymbol{P}_A)\\
&\times\psi_{n_AL_AM_{L_A}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\chi^{123}_{S_AM_{S_A}}\varphi_A^{123}\omega_A^{123}\\
&\times|q_1(\boldsymbol{k}_1)q_2(\boldsymbol{k}_2)q_3(\boldsymbol{k}_3)\rangle, \quad (2)
\end{aligned}
$$

$$
\begin{aligned}
&|B(n_{\rm B}^{2S_{\rm B}+1}L_{{\rm B}J_{\rm B}M_{J_{\rm B}}})(\boldsymbol{P}_{\rm B})\rangle \\
=&\sqrt{2E_{\rm B}}\sum_{M_{L_{\rm B}},M_{S_{\rm B}}}\langle L_{\rm B}M_{L_{\rm B}}S_{\rm B}M_{S_{\rm B}}|J_{\rm B}M_{J_{\rm B}}\rangle \\
&\times\int {\rm d}^3\boldsymbol{k}_a{\rm d}^3\boldsymbol{k}_{\rm b}\delta^3(\boldsymbol{k}_a+\boldsymbol{k}_{\rm b}-\boldsymbol{P}_{\rm B})\psi_{n_{\rm B}L_{\rm B}M_{L_{\rm B}}}(\boldsymbol{k}_{\rm a},\boldsymbol{k}_{\rm b}) \\
&\times\chi^{\rm ab}_{S_{\rm B}M_{S_{\rm B}}}\varphi^{\rm ab}_{\rm B}\omega^{\rm ab}_{\rm B}|q_{\rm a}(\boldsymbol{k}_{\rm a})q_{\rm b}(\boldsymbol{k}_{\rm b})\rangle, \qquad (3)
\end{aligned}
$$

both of which satisfy the normalization conditions

$$\langle {\rm A}(\boldsymbol{P}_{\rm A})|{\rm A}(\boldsymbol{P}'_{\rm A})\rangle = 2E_{\rm A}\delta^3(\boldsymbol{P}_{\rm A}-\boldsymbol{P}'_{\rm A}), \qquad (4)$$

$$\langle {\rm B}(\boldsymbol{P}_{\rm B})|{\rm B}(\boldsymbol{P}'_{\rm B})\rangle = 2E_{\rm B}\delta^3(\boldsymbol{P}_{\rm B}-\boldsymbol{P}'_{\rm B}), \qquad (5)$$

where the subscripts 1, 2, 3 denote the quarks of the parent hadron A, and a and b refer to the quark and antiquark within the meson B, respectively. $\boldsymbol{k}_{\rm i}$ (i=1, 2, 3, a, b) is the momentum of the quarks or antiquarks within the hadrons. And $\boldsymbol{P}_{\rm A}$ and $\boldsymbol{P}_{\rm B}$ represent the momentum of A and B, respectively. $S_{\rm A(B)}$ and $J_{\rm A(B)}$ denote the total spin and total angular momentum of the state A(B), respectively. The S-matrix of decay is defined as

$$S=I-{\rm i}2\pi\delta(E_{\rm f}-E_{\rm i})T. \qquad (6)$$

In the center of mass frame of baryon A, $\boldsymbol{P}_{\rm A}=0$ and $\boldsymbol{P}_{\rm B}=-\boldsymbol{P}_{\rm C}$. Finally, we can formulate the decay amplitude as

$$
\begin{aligned}
\mathcal{M}^{M_{J_{\rm A}}M_{J_{\rm B}}M_{J_{\rm C}}} &= \langle {\rm BC|T|A}\rangle \\
&=\gamma\sqrt{8E_{\rm A}E_{\rm B}E_{\rm C}}\sum_{\substack{M_{L_{\rm A}},M_{S_{\rm A}}\\ M_{L_{\rm B}},M_{S_{\rm B}}\\ M_{L_{\rm C}},M_{S_{\rm C}},m}}\langle L_{\rm A}M_{L_{\rm A}}S_{\rm A}M_{S_{\rm A}}|J_{\rm A}M_{J_{\rm A}}\rangle\langle L_{\rm B}M_{L_{\rm B}}S_{\rm B}M_{S_{\rm B}}|J_{\rm B}M_{J_{\rm B}}\rangle\langle 1m;1-m|00\rangle \\
&\quad\times\langle L_{\rm C}M_{L_{\rm C}}S_{\rm C}M_{S_{\rm C}}|J_{\rm C}M_{J_{\rm C}}\rangle\langle\chi^{235}_{S_{\rm C}M_{S_{\rm C}}}\chi^{14}_{S_{\rm B}M_{S_{\rm B}}}|\chi^{123}_{S_{\rm A}M_{S_{\rm A}}}\chi^{45}_{1-m}\rangle\langle\varphi^{235}_{\rm C}\varphi^{14}_{\rm B}|\varphi^{123}_{\rm A}\varphi^{45}_0\rangle I^{M_{L_{\rm A}},m}_{M_{L_{\rm B}},M_{L_{\rm C}}}(\boldsymbol{P}), \qquad (7)
\end{aligned}
$$

where the spatial integral $I^{M_{L_{\rm A}},m}_{M_{L_{\rm B}},M_{L_{\rm C}}}(\boldsymbol{p})$ is defined as

$$
\begin{aligned}
&I^{M_{L_{\rm A}},m}_{M_{L_{\rm B}},M_{L_{\rm C}}}(\boldsymbol{p}) \\
=&\int {\rm d}^3\boldsymbol{k}_1{\rm d}^3\boldsymbol{k}_2{\rm d}^3\boldsymbol{k}_3{\rm d}^3\boldsymbol{k}_4{\rm d}^3\boldsymbol{k}_5\delta^3(\boldsymbol{k}_4+\boldsymbol{k}_5) \\
&\times\delta^3(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3-\boldsymbol{P}_{\rm A})\delta^3(\boldsymbol{k}_1+\boldsymbol{k}_4-\boldsymbol{P}_{\rm B}) \\
&\times\delta^3(\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_5-\boldsymbol{P}_{\rm C}) \\
&\times\psi^*_{n_{\rm B}L_{\rm B}M_{L_{\rm B}}}(\boldsymbol{k}_1,\boldsymbol{k}_4)\psi^*_{n_{\rm C}L_{\rm C}M_{L_{\rm C}}}(\boldsymbol{k}_2,\boldsymbol{k}_3,\boldsymbol{k}_5) \\
&\times\psi_{n_{\rm A}L_{\rm A}M_{L_{\rm A}}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\mathcal{Y}^m_1\left(\frac{\boldsymbol{k}_4-\boldsymbol{k}_5}{2}\right). \qquad (8)
\end{aligned}
$$

and $\langle\chi^{235}_{S_{\rm C}M_{S_{\rm C}}}\chi^{14}_{S_{\rm B}M_{S_{\rm B}}}|\chi^{123}_{S_{\rm A}M_{S_{\rm A}}}\chi^{45}_{1-m}\rangle$ and $\langle\varphi^{235}_{\rm C}\varphi^{14}_{\rm B}|\varphi^{123}_{\rm A}\varphi^{45}_0\rangle$ denote the spin and flavor matrix element, respectively.

In the framework of the QPC model, the decay occurs through the recombination of the five quarks from the initial heavy baryon and the quark-antiquark pair created from the vacuum. There are three ways of recombination, that is,

$$\mathcal{A}({\rm q}_1,{\rm q}_2,{\rm Q}_3)+\mathcal{P}(\bar{\rm q}_4,{\rm q}_5)\to\mathcal{B}({\rm q}_2,{\rm Q}_3,{\rm q}_5)+\mathcal{C}({\rm q}_1,\bar{\rm q}_4), \qquad (9)$$

$$\mathcal{A}({\rm q}_1,{\rm q}_2,{\rm Q}_3)+\mathcal{P}(\bar{\rm q}_4,{\rm q}_5)\to\mathcal{B}({\rm q}_1,{\rm Q}_3,{\rm q}_5)+\mathcal{C}({\rm q}_2,\bar{\rm q}_4), \qquad (10)$$

$$\mathcal{A}({\rm q}_1,{\rm q}_2,{\rm Q}_3)+\mathcal{P}(\bar{\rm q}_4,{\rm q}_5)\to\mathcal{B}({\rm q}_1,{\rm q}_2,{\rm q}_5)+\mathcal{C}({\rm Q}_3,\bar{\rm q}_4). \qquad (11)$$

Here, Q denotes the heavy quark (b or c) and $\rm q_{\it i}$ is the light quark. When the excited heavy baryon decays into a heavy baryon plus a light meson, as shown in Eq. (9) and Eq. (10), the decay amplitude is enhanced by a factor of two:

$$
\begin{aligned}
&\mathcal{M}^{M_{J_{\rm A}}M_{J_{\rm B}}M_{J_{\rm C}}} \\
=&2\gamma\sqrt{8E_{\rm A}E_{\rm B}E_{\rm C}} \\
&\times\sum_{\substack{M_{L_{\rm A}},M_{S_{\rm A}}\\ M_{L_{\rm B}},M_{S_{\rm B}}\\ M_{L_{\rm C}},M_{S_{\rm C}},m}}\langle L_{\rm A}M_{L_{\rm A}}S_{\rm A}M_{S_{\rm A}}|J_{\rm A}M_{J_{\rm A}}\rangle \\
&\times\langle L_{\rm B}M_{L_{\rm B}}S_{\rm B}M_{S_{\rm B}}|J_{\rm B}M_{J_{\rm B}}\rangle \\
&\times\langle L_{\rm C}M_{L_{\rm C}}S_{\rm C}M_{S_{\rm C}}|J_{\rm C}M_{J_{\rm C}}\rangle \\
&\times\langle 1m;1-m|00\rangle\langle\chi^{235}_{S_{\rm C}M_{S_{\rm C}}}\chi^{14}_{S_{\rm B}M_{S_{\rm B}}}|\chi^{123}_{S_{\rm A}M_{S_{\rm A}}}\chi^{45}_{1-m}\rangle \\
&\times\langle\varphi^{235}_{\rm C}\varphi^{14}_{\rm B}|\varphi^{123}_{\rm A}\varphi^{45}_0\rangle I^{M_{L_{\rm A}},m}_{M_{L_{\rm B}},M_{L_{\rm C}}}(\boldsymbol{P}). \qquad (12)
\end{aligned}
$$

However, in the strong decays of $\Xi_{\rm b,c}$ or when the heavy baryon decays into a heavy meson plus a light baryon, only one way of arrangement is allowed. Hence, this prefactor two disappears.

The decay width of the process A→B+C is

$$\varGamma=\pi^2\frac{|p|}{M^2_{\rm A}}\frac{s}{2J_{\rm A}+1}|\mathcal{M}^{M_{J_{\rm A}}M_{J_{\rm B}}M_{J_{\rm C}}}|^2, \qquad (13)$$

where $|p|$ is the outgoing momentum of daughter baryon in the parent's center mass frame, and $s=1/(1+\delta_{\rm BC})$ is a statistical factor if B and C are identical particles.

The above formalism is only applicable to the two-body strong decays. We need to modify the above formalism in order to calculate the three-body dipion strong decay widths. We assume that the outgoing meson B is a resonant state of $(\pi\pi)^{I=0}_{l=0}$ or $(\pi\pi)^{I=1}_{l=1}$. Now, the decay width in Eq. (13) is a function of the mass of the outgoing "meson" state B. That is, the original two-body decay width becomes $\varGamma(m_{\rm B})$. As a resonant state of

$(\pi\pi)^{I=0}_{l=0}$ or $(\pi\pi)^{I=1}_{l=1}$, its mass satisfies the Breit-Wigner distribution. We need to convolute the $\Gamma(m_{\rm B})$ with the Breit-Wigner distribution to get the physical three-pion decay width of the initial particle A:

$$\Gamma_{\rm phy}=\int_{2m_\pi}^{M_{\rm A}-M_{\rm C}}\varrho(m_{\rm B})\Gamma(m_{\rm B}){\rm d}m_{\rm B}, \tag{14}$$

where $\Gamma(m_{\rm B})$ is the decay width of mesons given in the Eq. (13). $\varrho(m_{\rm B})$ is the Breit-Wigner mass distribution of the $(\pi\pi)^{I=0}_{l=0}$ or $(\pi\pi)^{I=1}_{l=1}$ resonance

$$\varrho(m_{\rm B})=\frac{\Gamma'}{2\pi[(m_{\rm B}-m_{\rm cen})^2+\Gamma'^2/4]}, \tag{15}$$

where $m_{\rm cen}$ and Γ' are the mass and decay width of the $\sigma(600)$ or $\rho(770)$ resonances, respectively.

3 Numerical results

The dipion decay widths of the heavy baryons from the QPC model involve several parameters: the strength of the quark pair creation from the vacuum γ, the R value in the harmonic oscillator wave function of the meson, and the $\alpha_{\rho,\lambda}$ in the baryon wave functions. There are two kinds of values for γ [10, 31–33]. We follow the convention of Ref. [33] and take $\gamma=13.4$, which is considered as a universal parameter in the $^3P_0$ model. The R value of $\sigma(600)$ mesons is 3.486 GeV^{-1} [34] while R=3.571 GeV^{-1} for the $\rho(770)$ meson [34]. For the proton and Λ $\alpha_\rho=\alpha_\lambda$=0.5 GeV [30]. For the S-wave heavy baryons, the parameters α_ρ and α_λ in the harmonic oscillator wave functions can be fixed to reproduce the mass splitting through the contact term in the potential model [35]. Their values are α_ρ=0.6 GeV and α_λ=0.6 GeV. For the P-wave and D-wave heavy baryons, α_ρ and α_λ are expected to lie in the range 0.5–0.7 GeV. In the following, our numerical results are obtained with the typical values $\alpha_\rho=\alpha_\lambda$=0.6 GeV.

For the three-body dipion strong decays, we also need the mass and width of $(\pi\pi)^{I=0}_{l=0}$ or $(\pi\pi)^{I=1}_{l=1}$, corresponding to $\sigma(600)$ or $\rho(770)$, which are given in Table 3. With the above preparation, we present the results of the dipion decay width of of the P-wave and D-wave excited heavy baryons.

Table 3. The resonance parameters of $\sigma(600)$ and $\rho(770)$ corresponding to $(\pi\pi)^{I=0}_{l=0}$ and $(\pi\pi)^{I=1}_{l=1}$, respectively.

particle	mass/MeV	width/MeV	R/GeV^{-1}
$\sigma(600)$	400	400	3.486 [34]
$\rho(770)$	770	149	3.571 [34]

3.1 1P states

As shown in Tables 1 and 2, only the P-wave excited $\Lambda_{\rm Q}$ (Q=b, c) states have so far been observed in the three-body dipion strong decay channel $\Lambda_{\rm Q}\pi^+\pi^-$, all of which have a small phase space. Here, we present the theoretical predictions of the three-body dipion strong decays of all the P-wave excited heavy baryons via the QPC model.

For $\Lambda_{\rm Q}$ (Q=b, c), the tiny phase space leads to a very small strong decay width, which is given in Table 4. Since the $(\pi\pi)^{I=0}_{l=0}$ pair arises from $\sigma(600)$, the dipion decay width of the heavy baryons depends on the value of the mass and decay width of $\sigma(600)$. We present the dependence of the strong decay width of $\Lambda_{\rm c}(2625)\to\Lambda_{\rm c}\pi^+\pi^-$ on the width and mass of $\sigma(600)$ in Table 4. The decay width of $\Lambda_{\rm c}(2625)\to\Lambda_{\rm c}\pi^+\pi^-$ depends on the width of $\sigma(600)$ strongly with $m_\sigma=400$ MeV. When increasing m_σ, this dependence becomes weaker.

Table 4. The strong decay width (in unit of keV) of $\Lambda^*_{\rm Q}\to\Lambda_{\rm Q}\pi^+\pi^-$ (Q=b, c) when taking different values of the width of $\sigma(600)$. Here, we fix the mass of $\sigma(600)$ as 400 MeV.

states	Γ'_σ/GeV			
	0.4	0.5	0.6	0.7
$\Lambda^*_c(2595)$	4.6	4	3.5	3.1
$\Lambda^*_c(2625)$	30.5	26.4	23.1	20.3
$\Lambda^*_{\rm b}(5912)$	0.77	0.68	0.6	0.53
$\Lambda^*_{\rm b}(5920)$	2.4	2.1	1.8	1.6

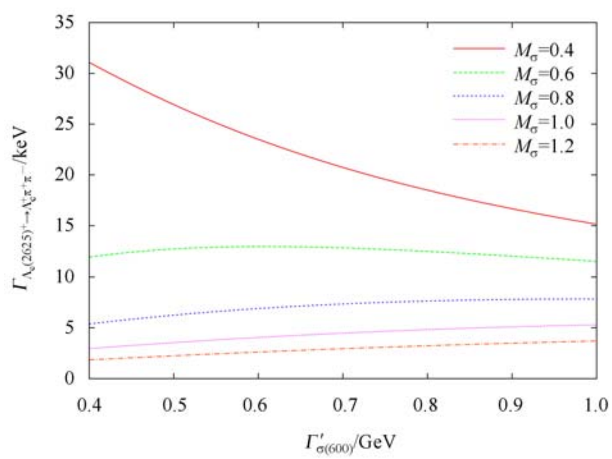

Fig. 1. The variation of the decay width of $\Lambda_{\rm c}(2625)\to\Lambda_{\rm c}\pi^+\pi^-$ with the resonance parameters of $\sigma(600)$.

In Tables 5–8, we list the dipion strong decay widths of the P-wave excited charmed baryons $\Xi_{\rm c}(2790)$, $\Xi_{\rm c}(2815)$, $\Sigma_{\rm c}(2800)$, and the P-wave excited states of $\Xi_{\rm b}$ and $\Sigma_{\rm b}$. The masses and quantum numbers of $\Xi_{\rm c}(2790)$ and $\Xi_{\rm c}(2815)$ are determined experimentally. However, at present there are no experimental data for the P-wave excited $\Xi_{\rm b}$ and $\Sigma_{\rm b}$. The quantum number of $\Sigma_{\rm c}(2800)$ remains unknown. So, we present the three-body dipion decay widths of $\Sigma_{\rm c}(2800)$ with different assignments and the three-body dipion decay widths of the P-wave excitations of Ξ_b and Σ_b under different assignments, where the corresponding mass is taken from Ref. [12] if there is no experimental information.

Table 5. The dipion decay widths of the P-wave excited $\Xi_c(2790)$ and $\Xi_c(2815)$ (in unit of MeV).

states	assignments	$I(J^P)$	$\Xi_c(\pi\pi)^{I=1}_{l=1}$	$\Xi_c(\pi\pi)^{I=0}_{l=0}$
$\Xi_c(2790)$	Ξ_{c1}	$\frac{1}{2}\left(\frac{1}{2}^-\right)$	0.003	0.001
$\Xi_c(2815)$	Ξ_{c1}	$\frac{1}{2}\left(\frac{3}{2}^-\right)$	0.007	0.002

Table 6. The dipion strong decay width of $\Sigma_c(2800)$ with different assignments (in unit of MeV).

assignments	$\Lambda_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma_c(\pi\pi)^{I=0}_{l=0}$
$\Sigma_{c0}\left(\frac{1}{2}^-\right)$	0	0.038	0.003
$\Sigma_{c1}\left(\frac{1}{2}^-\right)$	2.6	6.1×10^{-4}	0.002
$\Sigma_{c1}\left(\frac{3}{2}^-\right)$	2.6	3.1×10^{-4}	4.5×10^{-4}
$\Sigma_{c2}\left(\frac{3}{2}^-\right)$	0.078	0.38	0.11
$\Sigma_{c2}\left(\frac{5}{2}^-\right)$	0.078	1.2×10^{-4}	0
$\tilde{\Sigma}_{c1}\left(\frac{1}{2}^-\right)$	4.1	0.45	0.093
$\tilde{\Sigma}_{c1}\left(\frac{3}{2}^-\right)$	4.1	0.11	0.023

Table 7. The strong decay width of the P-wave excited Ξ_b with different assignments (in unit of MeV).

states	$\Xi_b(\pi\pi)^{I=1}_{l=1}$	$\Xi'_b(\pi\pi)^{I=1}_{l=1}$	$\Xi_b(\pi\pi)^{I=0}_{l=0}$
$\Xi_{b1}\left(\frac{1}{2}^-\right)$	0.005	0	0.001
$\Xi_{b1}\left(\frac{3}{2}^-\right)$	0.007	0	0.002
$\Xi'_{b0}\left(\frac{1}{2}^-\right)$	0	0.001	0
$\Xi'_{b1}\left(\frac{1}{2}^-\right)$	0.09	8×10^{-7}	0.061
$\Xi'_{b1}\left(\frac{3}{2}^-\right)$	0.089	3.5×10^{-7}	0.059
$\Xi'_{b2}\left(\frac{3}{2}^-\right)$	7.4×10^{-4}	0	0
$\Xi'_{b2}\left(\frac{5}{2}^-\right)$	8.9×10^{-4}	0	0
$\tilde{\Xi}'_{b1}\left(\frac{1}{2}^-\right)$	0.014	0	0.004
$\tilde{\Xi}'_{b1}\left(\frac{3}{2}^-\right)$	0.02	0	0.007
$\tilde{\Xi}_{b0}\left(\frac{1}{2}^-\right)$	0	0.002	0
$\tilde{\Xi}_{b1}\left(\frac{1}{2}^-\right)$	0.27	2.5×10^{-6}	0.18
$\tilde{\Xi}_{b1}\left(\frac{3}{2}^-\right)$	0.27	1.1×10^{-6}	0.18
$\tilde{\Xi}_{b2}\left(\frac{3}{2}^-\right)$	0.002	0	0
$\tilde{\Xi}_{b2}\left(\frac{5}{2}^-\right)$	0.002	0	0

Table 8. The dipion decay widths of the P-wave excited Σ_b states with different assignments (in unit of MeV).

states	$\Lambda_b(\pi\pi)^{I=1}_{l=1}$	$\Sigma_b(\pi\pi)^{I=1}_{l=1}$	$\Sigma_b(\pi\pi)^{I=0}_{l=0}$
$\Sigma_{b0}\left(\frac{1}{2}^-\right)$	0	0.012	0.001
$\Sigma_{b1}\left(\frac{1}{2}^-\right)$	2.3	5.4×10^{-6}	5×10^{-5}
$\Sigma_{b1}\left(\frac{3}{2}^-\right)$	2.2	1.7×10^{-6}	1×10^{-6}
$\Sigma_{b2}\left(\frac{3}{2}^-\right)$	0.031	0	0
$\Sigma_{b2}\left(\frac{5}{2}^-\right)$	0.036	0	0
$\tilde{\Sigma}_{b1}\left(\frac{1}{2}^-\right)$	3.6	0.057	0.003
$\tilde{\Sigma}_{b1}\left(\frac{3}{2}^-\right)$	3.6	0.014	0

Table 9. The three-body dipion strong decay width of $\Lambda_c(2880)$ as the D-wave excited states (in unit of MeV).

states	$\Sigma_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma^*_c(\pi\pi)^{I=1}_{l=1}$	$\Lambda_c(\pi\pi)^{I=0}_{l=0}$
$\Lambda_{c2}\left(\frac{5}{2}^+\right)$	0.002	0.002	2.4×10^{-3}
$\hat{\Lambda}_{c2}\left(\frac{5}{2}^+\right)$	0.02	0.018	0.002
$\check{\Lambda}^1_{c2}\left(\frac{5}{2}^+\right)$	0	0	0
$\check{\Lambda}^2_{c2}\left(\frac{5}{2}^+\right)$	0.002	0.007	0.3
$\check{\Lambda}^2_{c3}\left(\frac{5}{2}^+\right)$	0.12	0.006	0

3.2 1D states

Quite a few D-wave excited charmed baryons were observed experimentally, such as $\Lambda_c(2880)$ with $J^P=\frac{5}{2}^+$, $\Lambda_c(2940)$ with J^P still undetermined. Both $\Lambda_c(2880)$ and $\Lambda_c(2940)$ are considered as the D-wave excited states of Λ_c. Several other charmed baryons with undetermined J^P quantum numbers were also considered as the D-wave orbitally excited states, such as $\Xi_c(2980)$ and $\Xi_c(3080)$.

Here, we list the dipion decay width of $\Lambda_c(2880)$ with different assignments in Table 9 and that of $\Lambda_c(2940)$ in Table 10. The quantum numbers of the D-wave excited $\Xi_c(2980,3080,3055,3123)$ are not clear. We list their three-body decay width with different assignments of their inner quantum numbers. None of the D-wave excited Σ_c states and all the D-wave bottom baryons have been observed experimentally. So, we just give the their three-body dipion decay width in different assignments of their inner quantum numbers with their masses chosen from Ref. [12] (see Tables 11–18 for more details).

Table 10. The strong dipion decay width of $\Lambda_c(2940)$ as the D-wave excited states (in unit of MeV).

states	$\Sigma_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma^*_c(\pi\pi)^{I=1}_{l=1}$	$\Lambda_c(\pi\pi)^{I=0}_{l=0}$
$\Lambda_{c2}\left(\frac{3}{2}^+\right)$	0.011	0.002	7×10^{-3}
$\Lambda_{c2}\left(\frac{5}{2}^+\right)$	0.003	0.005	1×10^{-4}
$\hat{\Lambda}_{c2}\left(\frac{3}{2}^+\right)$	0.1	0.022	0.007
$\hat{\Lambda}_{c2}\left(\frac{5}{2}^+\right)$	0.03	0.045	0.007
$\check{\Lambda}_{c0}\left(\frac{1}{2}^+\right)$	0	0	0
$\check{\Lambda}_{c1}\left(\frac{1}{2}^+\right)$	0	0	0
$\check{\Lambda}_{c1}\left(\frac{3}{2}^+\right)$	0	0	0
$\check{\Lambda}_{c2}\left(\frac{3}{2}^+\right)$	0	0	0
$\check{\Lambda}_{c2}\left(\frac{5}{2}^+\right)$	0	0	0
$\check{\Lambda}^1_{c1}\left(\frac{1}{2}^+\right)$	1.9	0.13	0
$\check{\Lambda}^1_{c1}\left(\frac{3}{2}^+\right)$	0.23	0.64	0
$\check{\Lambda}^2_{c1}\left(\frac{1}{2}^+\right)$	0.016	0.007	0
$\check{\Lambda}^2_{c1}\left(\frac{3}{2}^+\right)$	0.013	0.008	0
$\check{\Lambda}^2_{c2}\left(\frac{3}{2}^+\right)$	0.045	0.004	0.65
$\check{\Lambda}^2_{c2}\left(\frac{5}{2}^+\right)$	0.004	0.017	0.65
$\check{\Lambda}^2_{c3}\left(\frac{5}{2}^+\right)$	0.18	0.016	0
$\check{\Lambda}^2_{c3}\left(\frac{7}{2}^+\right)$	3×10^{-4}	0.072	0

Table 11. The strong dipion decay width of the D-wave excited states of Σ_c (in unit of MeV).

assignments	$\Lambda_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma_c(\pi\pi)^{I=1}_{l=1}$	$\Sigma_c^*(\pi\pi)^{I=1}_{l=1}$	$\Sigma_c(\pi\pi)^{I=0}_{l=0}$	$\Sigma_c^*(\pi\pi)^{I=0}_{l=0}$
$\Sigma_{c1}\left(\frac{1}{2}^+\right)$	0.3	0.015	0.01	0	0.053
$\Sigma_{c1}\left(\frac{3}{2}^+\right)$	0.27	0.013	0.01	0.072	0.022
$\Sigma_{c2}\left(\frac{3}{2}^+\right)$	0.55	0.041	0.006	0.006	0.002
$\Sigma_{c2}\left(\frac{5}{2}^+\right)$	0.49	0.004	0.018	0.39	0.002
$\Sigma_{c3}\left(\frac{5}{2}^+\right)$	0.016	0.083	0.008	0.028	0.001
$\Sigma_{c3}\left(\frac{7}{2}^+\right)$	0.04	0	0.093	0	0.03
$\hat{\Sigma}_{c1}\left(\frac{1}{2}^+\right)$	2.7	0.14	0.096	0	0.48
$\hat{\Sigma}_{c1}\left(\frac{3}{2}^+\right)$	2.5	0.12	0.09	0.654	0.2
$\hat{\Sigma}_{c2}\left(\frac{3}{2}^+\right)$	4.9	0.37	0.054	0.06	0.02
$\hat{\Sigma}_{c2}\left(\frac{5}{2}^+\right)$	4.4	0.036	0.16	3.5	0.026
$\hat{\Sigma}_{c3}\left(\frac{5}{2}^+\right)$	0.15	0.75	0.073	0.25	0.016
$\hat{\Sigma}_{c3}\left(\frac{7}{2}^+\right)$	0.36	0.006	0.84	0	0.27
$\check{\Sigma}^0_{c0}\left(\frac{1}{2}^+\right)$	41	3.9	3.2	0	0
$\check{\Sigma}^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0
$\check{\Sigma}^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0
$\check{\Sigma}^2_{c2}\left(\frac{3}{2}^+\right)$	2.3	0.37	0.11	0.35	0.11
$\check{\Sigma}^2_{c2}\left(\frac{5}{2}^+\right)$	2.1	0.1	0.19	0.13	0.14

Table 12. The strong dipion decay width of $\Xi_c(2980)$ as the D-wave excited states (in unit of MeV).

states	$\Xi_c(\pi\pi)^{I=1}_{l=1}$	$\Xi'_c(\pi\pi)^{I=1}_{l=1}$	$\Xi^{*\prime}_c(\pi\pi)^{I=1}_{l=1}$	$\Xi_c(\pi\pi)^{I=0}_{l=0}$	$\Xi'_c(\pi\pi)^{I=0}_{l=0}$	$\Xi^{*\prime}_c(\pi\pi)^{I=0}_{l=0}$
$\Xi_{c2}\left(\frac{3}{2}^+\right)$	0.001	2.9×10^{-4}	2×10^{-5}	9.8×10^{-6}	1.1×10^{-4}	4.5×10^{-6}
$\Xi_{c2}\left(\frac{5}{2}^+\right)$	0.001	8×10^{-5}	4×10^{-5}	9.8×10^{-6}	4.9×10^{-5}	7×10^{-6}
$\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$	0.016	0.002	1.9×10^{-4}	8.8×10^{-5}	0.001	4×10^{-5}
$\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$	0.016	7.6×10^{-4}	3.7×10^{-4}	8.8×10^{-5}	0.004	6.2×10^{-5}
$\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$	0.12	0.047	0.001	0	0.66	0
$\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$	0.12	0.005	0.005	0	0	0.15
$\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$	0.008	4.1×10^{-4}	5×10^{-5}	0	0	7.7×10^{-5}
$\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$	0.008	3×10^{-4}	5×10^{-5}	0	9×10^{-4}	3.8×10^{-5}
$\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$	0.016	0.001	3×10^{-5}	0.019	9.2×10^{-5}	3.9×10^{-6}
$\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$	0.016	9×10^{-5}	1.4×10^{-4}	0.019	4.1×10^{-5}	6.1×10^{-6}
$\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$	2.4×10^{-4}	0.004	6×10^{-4}	0	7.5×10^{-4}	8.5×10^{-6}
$\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$	2.4×10^{-4}	2×10^{-6}	6×10^{-4}	0	0	3.8×10^{-5}
$\Xi'_{c1}\left(\frac{1}{2}^+\right)$	0.001	6×10^{-5}	1×10^{-5}	0	0	1.3×10^{-5}
$\Xi'_{c1}\left(\frac{3}{2}^+\right)$	0.001	5×10^{-5}	1×10^{-5}	0	1.6×10^{-4}	6.4×10^{-6}
$\Xi'_{c2}\left(\frac{3}{2}^+\right)$	0.002	2×10^{-4}	6×10^{-6}	0.003	1.5×10^{-5}	6.5×10^{-7}
$\Xi'_{c2}\left(\frac{5}{2}^+\right)$	0.002	1×10^{-5}	2×10^{-5}	0.003	6.8×10^{-6}	1×10^{-6}
$\Xi'_{c3}\left(\frac{5}{2}^+\right)$	4×10^{-5}	8×10^{-4}	2×10^{-5}	0	1.2×10^{-4}	1.4×10^{-6}
$\Xi'_{c3}\left(\frac{7}{2}^+\right)$	4×10^{-5}	4×10^{-7}	1×10^{-4}	0	0	6.4×10^{-6}
$\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$	0.013	6×10^{-4}	8×10^{-5}	0	0	1×10^{-4}
$\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$	0.013	4×10^{-4}	1×10^{-4}	0	0.001	5×10^{-5}
$\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$	0.024	0.001	5×10^{-5}	0.03	1.3×10^{-4}	5.8×10^{-6}
$\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$	0.024	1×10^{-4}	2×10^{-4}	0.03	6×10^{-5}	9.1×10^{-6}
$\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$	4×10^{-4}	0.007	2×10^{-4}	0	0.001	1×10^{-5}
$\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$	4×10^{-4}	3×10^{-6}	9×10^{-4}	0	0	5×10^{-5}
$\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$	0.19	0.016	0.003	2.2	0	0
$\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$	0.011	0.001	1×10^{-4}	5×10^{-5}	6.6×10^{-4}	2×10^{-5}
$\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$	0.011	5×10^{-4}	2×10^{-4}	5.8×10^{-5}	2.9×10^{-4}	4.1×10^{-5}

Table 13. The strong dipion decay width of $\Xi_c(3055)$ as the D-wave excited states (in unit of MeV).

states	$\Xi_c(\pi\pi)^{I=1}_{l=1}$	$\Xi'_c(\pi\pi)^{I=1}_{l=1}$	$\Xi^{*\prime}_c(\pi\pi)^{I=1}_{l=1}$	$\Xi_c(\pi\pi)^{I=0}_{l=0}$	$\Xi'_c(\pi\pi)^{I=0}_{l=0}$	$\Xi^{*\prime}_c(\pi\pi)^{I=0}_{l=0}$
$\Xi_{c2}\left(\frac{3}{2}^+\right)$	0.004	0.001	2×10^{-4}	5.4×10^{-5}	8.6×10^{-4}	1.4×10^{-4}
$\Xi_{c2}\left(\frac{5}{2}^+\right)$	0.004	3×10^{-4}	5×10^{-4}	5.4×10^{-5}	3.8×10^{-4}	2.2×10^{-4}
$\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$	0.044	0.011	0.002	4.9×10^{-4}	0.008	0.001
$\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$	0.044	0.003	0.004	4.9×10^{-4}	0.003	0.002
$\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$	0.34	0.213	0.013	0	1.7	0
$\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$	0.34	0.025	0.063	0	0	0.74
$\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$	0.023	0.001	7×10^{-4}	0	0	0.002
$\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$	0.023	0.001	8×10^{-4}	0	0.007	0.001
$\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$	0.043	0.005	4×10^{-4}	0.069	6×10^{-4}	1×10^{-4}
$\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$	0.043	4×10^{-4}	0.001	0.069	3×10^{-4}	2×10^{-4}
$\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$	0.001	0.02	0.001	0	0.006	3×10^{-4}
$\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$	0.001	3×10^{-5}	0.007	0	0	0.001
$\Xi'_{c1}\left(\frac{1}{2}^+\right)$	0.004	3×10^{-4}	1×10^{-4}	0	0	4×10^{-4}
$\Xi'_{c1}\left(\frac{3}{2}^+\right)$	0.004	2.5×10^{-4}	1.4×10^{-4}	0	0.001	2×10^{-2}
$\Xi'_{c2}\left(\frac{3}{2}^+\right)$	0.007	8×10^{-4}	7×10^{-5}	0.01	1×10^{-4}	1.9×10^{-5}
$\Xi'_{c2}\left(\frac{5}{2}^+\right)$	0.007	7×10^{-5}	3×10^{-4}	0.01	4.9×10^{-5}	3×10^{-5}
$\Xi'_{c3}\left(\frac{5}{2}^+\right)$	2×10^{-4}	0.003	3×10^{-4}	0	0.001	4.6×10^{-5}
$\Xi'_{c3}\left(\frac{7}{2}^+\right)$	2×10^{-4}	6×10^{-6}	0.001	0	0	2.1×10^{-4}
$\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$	0.035	0.002	0.001	0	0	0.004
$\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$	0.035	0.002	0.001	0	0.012	0.002
$\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$	0.065	0.007	7×10^{-4}	0.1	0.001	1.7×10^{-4}
$\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$	0.065	7×10^{-4}	0.002	0.1	4.5×10^{-4}	2.7×10^{-4}
$\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$	0.001	0.03	0.002	0	0.009	4×10^{-4}
$\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$	0.001	5×10^{-5}	0.01	0	0	0.001
$\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$	0.51	0.075	0.039	3.7	0	0
$\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$	0.029	0.007	0.001	3×10^{-4}	0.005	8×10^{-4}
$\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$	0.029	0.002	0.003	3×10^{-4}	0.002	0.001

Table 14. The strong dipion decay width of $\Xi_c(3080)$ as the D-wave excited states (in unit of MeV).

states	$\Xi_c(\pi\pi)^{I=1}_{l=1}$	$\Xi'_c(\pi\pi)^{I=1}_{l=1}$	$\Xi^{*\prime}_c(\pi\pi)^{I=1}_{l=1}$	$\Xi_c(\pi\pi)^{I=0}_{l=0}$	$\Xi'_c(\pi\pi)^{I=0}_{l=0}$	$\Xi^{*\prime}_c(\pi\pi)^{I=0}_{l=0}$
$\Xi_{c2}\left(\frac{3}{2}^+\right)$	0.006	0.001	4×10^{-4}	9×10^{-5}	0.001	3×10^{-4}
$\Xi_{c2}\left(\frac{5}{2}^+\right)$	0.006	6×10^{-4}	8×10^{-4}	9×10^{-5}	6.5×10^{-4}	4.7×10^{-4}
$\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$	0.06	0.017	0.004	8×10^{-4}	0.013	0.003
$\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$	0.06	0.005	0.007	8×10^{-4}	0.006	0.004
$\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$	0.46	0.32	0.022	0	2.120	0
$\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$	0.46	0.037	0.11	0	0	1
$\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$	0.031	0.002	0.001	0	0	0.005
$\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$	0.031	0.002	0.001	0	0.011	0.002
$\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$	0.058	0.007	8×10^{-4}	0.098	0.001	2×10^{-4}
$\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$	0.058	7×10^{-4}	0.002	0.098	5×10^{-4}	4×10^{-4}
$\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$	0.002	0.03	0.002	0	0.01	6×10^{-4}
$\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$	0.002	6×10^{-5}	0.012	0	0	0.002
$\Xi'_{c1}\left(\frac{1}{2}^+\right)$	0.005	4×10^{-4}	2×10^{-4}	0	0	8.4×10^{-4}
$\Xi'_{c1}\left(\frac{3}{2}^+\right)$	0.005	4×10^{-4}	3×10^{-4}	0	0.002	4.2×10^{-4}
$\Xi'_{c2}\left(\frac{3}{2}^+\right)$	0.009	0.001	1×10^{-4}	0.016	1.8×10^{-4}	4×10^{-5}
$\Xi'_{c2}\left(\frac{5}{2}^+\right)$	0.009	1×10^{-4}	5×10^{-4}	0.016	8×10^{-4}	6×10^{-5}
$\Xi'_{c3}\left(\frac{5}{2}^+\right)$	4×10^{-4}	0.005	4×10^{-4}	0	0.002	9.8×10^{-5}
$\Xi'_{c3}\left(\frac{7}{2}^+\right)$	4×10^{-4}	1×10^{-5}	0.002	0	0	4×10^{-4}
$\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$	0.047	0.004	0.001	0	0	0.007
$\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$	0.047	0.003	0.002	0	0.018	0.004
$\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$	0.087	0.011	0.001	0.15	1.7×10^{-3}	3.6×10^{-4}
$\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$	0.087	0.001	0.004	0.15	7.3×10^{-4}	5.7×10^{-4}
$\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$	0.003	0.045	0.004	0	0.015	8.8×10^{-4}
$\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$	0.003	1×10^{-4}	0.018	0	0	3.9×10^{-3}
$\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$	0.69	0.11	0.068	4.3	0	0
$\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$	0.04	0.011	0.002	5×10^{-4}	0.008	0.001
$\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$	0.04	0.003	0.005	5×10^{-4}	0.003	0.002

Table 15. The strong dipion decay width of $\Xi_c(3123)$ as the D-wave excited states (in unit of MeV).

states	$\Xi_c(\pi\pi)^{I=1}_{l=1}$	$\Xi'_c(\pi\pi)^{I=1}_{l=1}$	$\Xi^{*\prime}_c(\pi\pi)^{I=1}_{l=1}$	$\Xi_c(\pi\pi)^{I=0}_{l=0}$	$\Xi'_c(\pi\pi)^{I=0}_{l=0}$	$\Xi^{*\prime}_c(\pi\pi)^{I=0}_{l=0}$
$\Xi_{c2}\left(\frac{3}{2}^+\right)$	0.011	0.003	9×10^{-4}	2×10^{-4}	3.2×10^{-3}	8.7×10^{-4}
$\Xi_{c2}\left(\frac{5}{2}^+\right)$	0.011	0.001	0.001	2×10^{-4}	1.4×10^{-3}	1.3×10^{-3}
$\hat{\Xi}_{c2}\left(\frac{3}{2}^+\right)$	0.099	0.031	0.008	1.7×10^{-3}	0.028	7.8×10^{-3}
$\hat{\Xi}_{c2}\left(\frac{5}{2}^+\right)$	0.099	0.009	0.016	1.7×10^{-3}	0.012	0.012
$\check{\Xi}^1_{c0}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{c2}\left(\frac{5}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^0_{c1}\left(\frac{1}{2}^+\right)$	0.76	0.59	0.05	0	3	0
$\check{\Xi}^0_{c1}\left(\frac{3}{2}^+\right)$	0.76	0.069	0.24	0	0	1.7
$\check{\Xi}^2_{c1}\left(\frac{1}{2}^+\right)$	0.051	0.004	0.003	0	0	0.014
$\check{\Xi}^2_{c1}\left(\frac{3}{2}^+\right)$	0.051	0.004	0.003	0	0.025	0.007
$\check{\Xi}^2_{c2}\left(\frac{3}{2}^+\right)$	0.095	0.013	0.001	0.17	0.002	6×10^{-4}
$\check{\Xi}^2_{c2}\left(\frac{5}{2}^+\right)$	0.095	0.001	0.006	0.17	0.001	0.001
$\check{\Xi}^2_{c3}\left(\frac{5}{2}^+\right)$	0.004	0.055	0.006	0	0.022	0.001
$\check{\Xi}^2_{c3}\left(\frac{7}{2}^+\right)$	0.004	2×10^{-4}	0.026	0	0	0.007
$\Xi'_{c1}\left(\frac{1}{2}^+\right)$	0.008	8×10^{-4}	5×10^{-4}	0	0	2.4×10^{-3}
$\Xi'_{c1}\left(\frac{3}{2}^+\right)$	0.008	7×10^{-4}	6×10^{-4}	0	4.3×10^{-3}	1.2×10^{-3}
$\Xi'_{c2}\left(\frac{3}{2}^+\right)$	0.015	0.002	3×10^{-4}	0.028	3.8×10^{-4}	1.1×10^{-4}
$\Xi'_{c2}\left(\frac{5}{2}^+\right)$	0.015	3×10^{-4}	0.001	0.028	1.7×10^{-4}	1.7×10^{-4}
$\Xi'_{c3}\left(\frac{5}{2}^+\right)$	8×10^{-4}	0.009	0.001	0	3.8×10^{-3}	2.9×10^{-4}
$\Xi'_{c3}\left(\frac{7}{2}^+\right)$	8×10^{-4}	3×10^{-4}	0.004	0	0	1.3×10^{-3}
$\hat{\Xi}'_{c1}\left(\frac{1}{2}^+\right)$	0.076	0.007	0.004	0	0	0.021
$\hat{\Xi}'_{c1}\left(\frac{3}{2}^+\right)$	0.076	0.006	0.005	0	0.038	0.01
$\hat{\Xi}'_{c2}\left(\frac{3}{2}^+\right)$	0.14	0.02	0.002	0.25	3.4×10^{-3}	1×10^{-3}
$\hat{\Xi}'_{c2}\left(\frac{5}{2}^+\right)$	0.14	0.002	0.009	0.25	1.5×10^{-3}	1.5×10^{-3}
$\hat{\Xi}'_{c3}\left(\frac{5}{2}^+\right)$	0.007	0.082	0.009	0	0.034	2.6×10^{-3}
$\hat{\Xi}'_{c3}\left(\frac{7}{2}^+\right)$	0.007	3×10^{-5}	0	0	0	0.012
$\check{\Xi}'^0_{c0}\left(\frac{1}{2}^+\right)$	1.14	0.21	0.15	5.2	0	0
$\check{\Xi}'^1_{c1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^1_{c1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^2_{c2}\left(\frac{3}{2}^+\right)$	0.066	0.02	0.005	0.001	0.019	0.005
$\check{\Xi}'^2_{c2}\left(\frac{5}{2}^+\right)$	0.066	0.006	0.011	0.001	0.008	0.008

Table 16. The strong dipion decay width of the D-wave excited states of $\Lambda_{\rm b}$ (in unit of MeV).

states	$\Sigma_{\rm c}\,(\pi\pi)^{I=1}_{l=1}$	$\Sigma^*_{\rm c}\,(\pi\pi)^{I=1}_{l=1}$	$\Lambda_{\rm c}\,(\pi\pi)^{I=0}_{l=0}$
$\Lambda_{\rm b2}\left(\frac{3}{2}^+\right)$	0.003	0.001	2.6×10^{-4}
$\Lambda_{\rm b2}\left(\frac{5}{2}^+\right)$	0.001	0.003	3.1×10^{-4}
$\hat{\Lambda}_{\rm b2}\left(\frac{3}{2}^+\right)$	0.029	0.01	2.3×10^{-3}
$\hat{\Lambda}_{\rm b2}\left(\frac{5}{2}^+\right)$	0.01	0.027	2.8×10^{-3}
$\check{\Lambda}_{\rm b0}\left(\frac{1}{2}^+\right)$	0	0	0
$\check{\Lambda}_{\rm b1}\left(\frac{1}{2}^+\right)$	0	0	0
$\check{\Lambda}_{\rm b1}\left(\frac{3}{2}^+\right)$	0	0	0
$\check{\Lambda}_{\rm b2}\left(\frac{3}{2}^+\right)$	0	0	0
$\check{\Lambda}_{\rm b2}\left(\frac{5}{2}^+\right)$	0	0	0
$\check{\Lambda}^1_{\rm b1}\left(\frac{1}{2}^+\right)$	0.52	0.061	0
$\check{\Lambda}^1_{\rm b1}\left(\frac{3}{2}^+\right)$	0.061	0.29	0
$\check{\Lambda}^2_{\rm b1}\left(\frac{1}{2}^+\right)$	0.004	0.003	0
$\check{\Lambda}^2_{\rm b1}\left(\frac{3}{2}^+\right)$	0.003	0.004	0
$\check{\Lambda}^2_{\rm b2}\left(\frac{3}{2}^+\right)$	0.012	0.002	0.32
$\check{\Lambda}^2_{\rm b2}\left(\frac{5}{2}^+\right)$	0.001	0.01	0.36
$\check{\Lambda}^2_{\rm b3}\left(\frac{5}{2}^+\right)$	0.065	0.009	0
$\check{\Lambda}^2_{\rm b3}\left(\frac{7}{2}^+\right)$	3×10^{-5}	0.044	0

Table 17. The strong dipion decay width of the D-wave excited states of $\Sigma_{\rm b}$ (in unit of MeV).

assignments	$\Lambda_{\rm b}(\pi\pi)^{I=1}_{l=1}$	$\Sigma_{\rm b}(\pi\pi)^{I=1}_{l=1}$	$\Sigma^*_{\rm b}(\pi\pi)^{I=1}_{l=1}$	$\Sigma_{\rm b}(\pi\pi)^{I=0}_{l=0}$	$\Sigma^*_{\rm b}(\pi\pi)^{I=0}_{l=0}$
$\Sigma_{\rm b1}\left(\frac{1}{2}^+\right)$	0.24	0.007	0.009	0	0.045
$\Sigma_{\rm b1}\left(\frac{3}{2}^+\right)$	0.1	0.001	0.002	6×10^{-3}	3×10^{-3}
$\Sigma_{\rm b2}\left(\frac{3}{2}^+\right)$	0.4	0.018	0.004	2.7×10^{-3}	1.7×10^{-3}
$\Sigma_{\rm b2}\left(\frac{5}{2}^+\right)$	0.35	0.001	0.013	9.4×10^{-4}	2×10^{-3}
$\Sigma_{\rm b3}\left(\frac{5}{2}^+\right)$	0.013	0.035	0.006	0.009	1.3×10^{-3}
$\Sigma_{\rm b3}\left(\frac{7}{2}^+\right)$	0.017	6×10^{-5}	0.038	0	0.009
$\hat{\Sigma}_{\rm b1}\left(\frac{1}{2}^+\right)$	2.1	0.069	0.081	0	0.4
$\hat{\Sigma}_{\rm b1}\left(\frac{3}{2}^+\right)$	0.93	0.013	0.019	0.051	0.025
$\hat{\Sigma}_{\rm b2}\left(\frac{3}{2}^+\right)$	3.63	0.17	0.042	0.024	0.015
$\hat{\Sigma}_{\rm b2}\left(\frac{5}{2}^+\right)$	3.2	0.012	0.12	0.008	0.018
$\hat{\Sigma}_{\rm b3}\left(\frac{5}{2}^+\right)$	0.12	0.32	0.058	0.078	0.012
$\hat{\Sigma}_{\rm b3}\left(\frac{7}{2}^+\right)$	0.16	6×10^{-4}	0.35	0	0.082
$\check{\Sigma}^0_{\rm b0}\left(\frac{1}{2}^+\right)$	32	1.93	2.7	0	0
$\check{\Sigma}^1_{\rm b1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0
$\check{\Sigma}^1_{\rm b1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0
$\check{\Sigma}^2_{\rm b2}\left(\frac{3}{2}^+\right)$	0.82	0.053	0.023	0.026	0.013
$\check{\Sigma}^2_{\rm b2}\left(\frac{5}{2}^+\right)$	1.49	0.041	0.14	0.044	0.091

Table 18. The strong dipion decay width of the D-wave excited states of Ξ_b (in unit of MeV).

states	$\Xi_b(\pi\pi)^{I=1}_{l=1}$	$\Xi'_b(\pi\pi)^{I=1}_{l=1}$	$\Xi^{*\prime}_b(\pi\pi)^{I=1}_{l=1}$	$\Xi_b(\pi\pi)^{I=0}_{l=0}$	$\Xi'_b(\pi\pi)^{I=0}_{l=0}$	$\Xi^{*\prime}_b(\pi\pi)^{I=0}_{l=0}$
$\Xi_{b2}\left(\frac{3}{2}^+\right)$	0.005	6×10^{-4}	2×10^{-4}	6.7×10^{-5}	2.8×10^{-4}	1.1×10^{-4}
$\Xi_{b2}\left(\frac{5}{2}^+\right)$	0.005	2×10^{-4}	5×10^{-4}	7.6×10^{-5}	1.4×10^{-4}	2.2×10^{-4}
$\hat{\Xi}_{b2}\left(\frac{3}{2}^+\right)$	0.047	0.005	0.001	6×10^{-4}	2.5×10^{-3}	1×10^{-3}
$\hat{\Xi}_{b2}\left(\frac{5}{2}^+\right)$	0.051	0.001	0.004	6.8×10^{-4}	1.3×10^{-3}	2×10^{-3}
$\check{\Xi}^1_{b0}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{b1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{b1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{b2}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^1_{b2}\left(\frac{5}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}^0_{b1}\left(\frac{1}{2}^+\right)$	0.36	0.092	0.011	0	2.1	0
$\check{\Xi}^0_{b1}\left(\frac{3}{2}^+\right)$	0.36	0.01	0.055	0	0	1.4
$\check{\Xi}^2_{b1}\left(\frac{1}{2}^+\right)$	0.024	8×10^{-4}	6×10^{-4}	0	0	0.012
$\check{\Xi}^2_{b1}\left(\frac{3}{2}^+\right)$	0.024	6×10^{-4}	7×10^{-4}	0	0.008	0.004
$\check{\Xi}^2_{b2}\left(\frac{3}{2}^+\right)$	0.045	0.002	4×10^{-4}	0.17	8×10^{-4}	4×10^{-4}
$\check{\Xi}^2_{b2}\left(\frac{5}{2}^+\right)$	0.049	2×10^{-4}	0.001	0.15	3×10^{-4}	6×10^{-4}
$\check{\Xi}^2_{b3}\left(\frac{5}{2}^+\right)$	0.001	0.01	0.001	0	0.006	9×10^{-4}
$\check{\Xi}^2_{b3}\left(\frac{7}{2}^+\right)$	0.001	1×10^{-5}	0.007	0	0	0.002
$\Xi'_{b1}\left(\frac{1}{2}^+\right)$	0.008	4×10^{-4}	4×10^{-4}	0	0	2×10^{-3}
$\Xi'_{b1}\left(\frac{3}{2}^+\right)$	0.007	3×10^{-4}	4×10^{-4}	0	1.4×10^{-3}	7.9×10^{-4}
$\Xi'_{b2}\left(\frac{3}{2}^+\right)$	0.014	0.001	2×10^{-4}	0.028	1.4×10^{-4}	7.9×10^{-5}
$\Xi'_{b2}\left(\frac{5}{2}^+\right)$	0.013	8×10^{-5}	7×10^{-4}	0.025	5×10^{-5}	9.7×10^{-5}
$\Xi'_{b3}\left(\frac{5}{2}^+\right)$	4×10^{-4}	0.002	4×10^{-4}	0	5.4×10^{-4}	7.1×10^{-5}
$\Xi'_{b3}\left(\frac{7}{2}^+\right)$	5×10^{-4}	4×10^{-6}	0.002	0	0	4.8×10^{-4}
$\hat{\Xi}'_{b1}\left(\frac{1}{2}^+\right)$	0.076	0.003	0.003	0	0	0.018
$\hat{\Xi}'_{b1}\left(\frac{3}{2}^+\right)$	0.068	0.002	0.003	0	0.013	7.1×10^{-3}
$\hat{\Xi}'_{b2}\left(\frac{3}{2}^+\right)$	0.13	0.009	0.002	0.26	1.3×10^{-3}	7.1×10^{-4}
$\hat{\Xi}'_{b2}\left(\frac{5}{2}^+\right)$	0.12	7×10^{-4}	0.006	0.23	4.7×10^{-4}	8.8×10^{-4}
$\hat{\Xi}'_{b3}\left(\frac{5}{2}^+\right)$	0.003	0.019	0.003	0	4.9×10^{-3}	6×10^{-4}
$\hat{\Xi}'_{b3}\left(\frac{7}{2}^+\right)$	0.004	3×10^{-5}	0.019	0	0	4×10^{-3}
$\check{\Xi}'^0_{b0}\left(\frac{1}{2}^+\right)$	1.14	0.104	0.13	4.1	0	0
$\check{\Xi}'^1_{b1}\left(\frac{1}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^1_{b1}\left(\frac{3}{2}^+\right)$	0	0	0	0	0	0
$\check{\Xi}'^2_{b2}\left(\frac{3}{2}^+\right)$	0.06	0.009	0.004	0	0.001	0
$\check{\Xi}'^2_{b2}\left(\frac{5}{2}^+\right)$	0.054	0.002	0.007	0	0	0.001

4 Discussion and conclusion

We have performed a systematic investigation of a special class of the dipion strong decays of the excited heavy baryons, where the two pions are from the intermediate rho or sigma mesons.

The dipion decay width of the heavy baryons is sensitive to the value of the strength of the quark-pair creation from the vacuum since the decay width $\Gamma \propto \gamma^2$. However, the dependence of the dipion decay width on the value of $\alpha_{\lambda,\rho}$ and R is weak [10]. Some dipion decay modes are forbidden by symmetry and their dipion decay widths are listed as zero in the tables.

The P-wave excited state $\Sigma_c(2800)$ and most of the D-wave excited states $\Lambda_c(2940)$ and Ξ_c (2980, 3080, 3055, 3123) were reported with their quantum numbers undetermined. A systematic investigation of their two-body strong decays was presented in Ref. [10], which may be helpful to the identification of their quantum numbers. Our present work investigated the dipion decay width of these particles with different inner structure assignments. For example, the dipion decay width of $\Sigma_c(2800)$ with different internal structures varies from 1 keV to several MeV, as shown in Table 6, which provides valuable clues to their underlying structure and quantum numbers. Unfortunately, none of the dipion decay modes have been experimentally observed for these states.

The $\Sigma_c\pi$ mode is the dominant decay mode of the P-wave excited Λ_c baryon. In contrast, the $\Sigma_b\pi$ mode is kinematically forbidden for the P-wave excited Λ_b baryon. Moreover, the conservation of the isospin symmetry forbids the $\Lambda_b\pi$ decay mode. In other words, the dipion decay channel becomes the dominant mode for the P-wave excited Λ_b heavy baryons. Because of the tiny phase space, the dipion strong decay width of these excited states is very small and is less than 5 keV, which may be comparable to its electromagnetic decay width. In other words, these two P-wave Λ_b baryons are extremely narrow resonances, which may be the most narrow baryon resonances up to now.

We notice that the different internal structure of the heavy baryon leads to very different dipion strong decay widths, even if their J^P quantum numbers are the same. For example, the dipion strong decay patterns of the three $J^P = \frac{1}{2}^-$ Σ_c states are very different. In other words, the dipion decay modes are very useful tools to probe the underlying structure of the excited heavy baryons. Hopefully, the present work will be helpful to the future experimental search of the excited heavy baryons, and the assignment of their quantum numbers and internal structures.

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